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(71) Applicant(s)
BlazePhotonics Limited
(Incorporated in the United Kingdom)
Finance Office University of Bath,
The Avenue, Claverton Down, BATH,
BA2 7AY, United Kingdom

(72) Inventor(s)
Brian Joseph Mangan
Jonathan Cave Knight
Timothy Adam Birks
Philip St.John Russell

(74) Agent and/or Address for Service
Abel & Imray
20 Red Lion Street, LONDON, WC1R 4PQ,
United Kingdom

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(54) Abstract Title

Microstructured optical fibre

(57) A method of manufacturing an optical fibre comprises:

(a) providing an elongate element comprising (i) a core region 310, (ii) a cladding region 320 that surrounds the core region and that includes a plurality of elongate holes 315, (iii) a higher-index zone that comprises dielectric material having a first, higher refractive index and (iv) a lower-index zone that surrounds the higher-index zone and comprises dielectric material having a second, lower refractive index.

(b) at least partially collapsing the holes in a length of the element to provide a collapsed portion comprising a core region, formed from the higher-index zone of the elongate element, and a cladding region, formed from the lower-index zone of the elongate element, such that the core region in the collapsed portion has a refractive index that is higher than the refractive index of the cladding region in the collapsed portion.

Collapse of the elongate holes in a microstructured optic fibre may cause a spot size of a guided mode to change by more than 20%. More than 90% of the power of a guided mode may propagate in an inner core region.

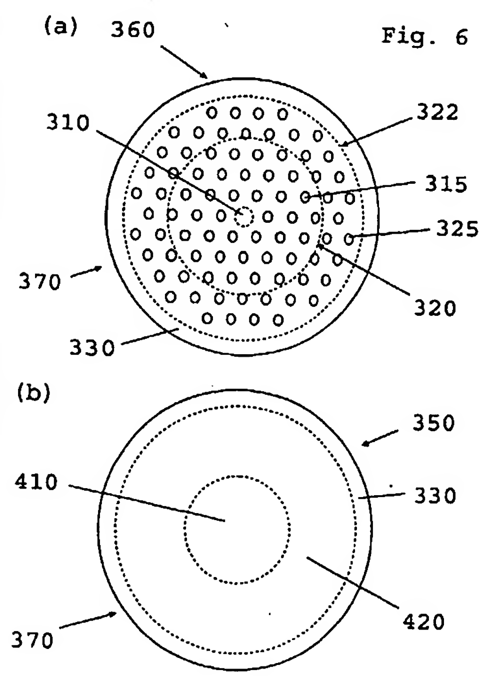

Fig. 6

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Fig. 1

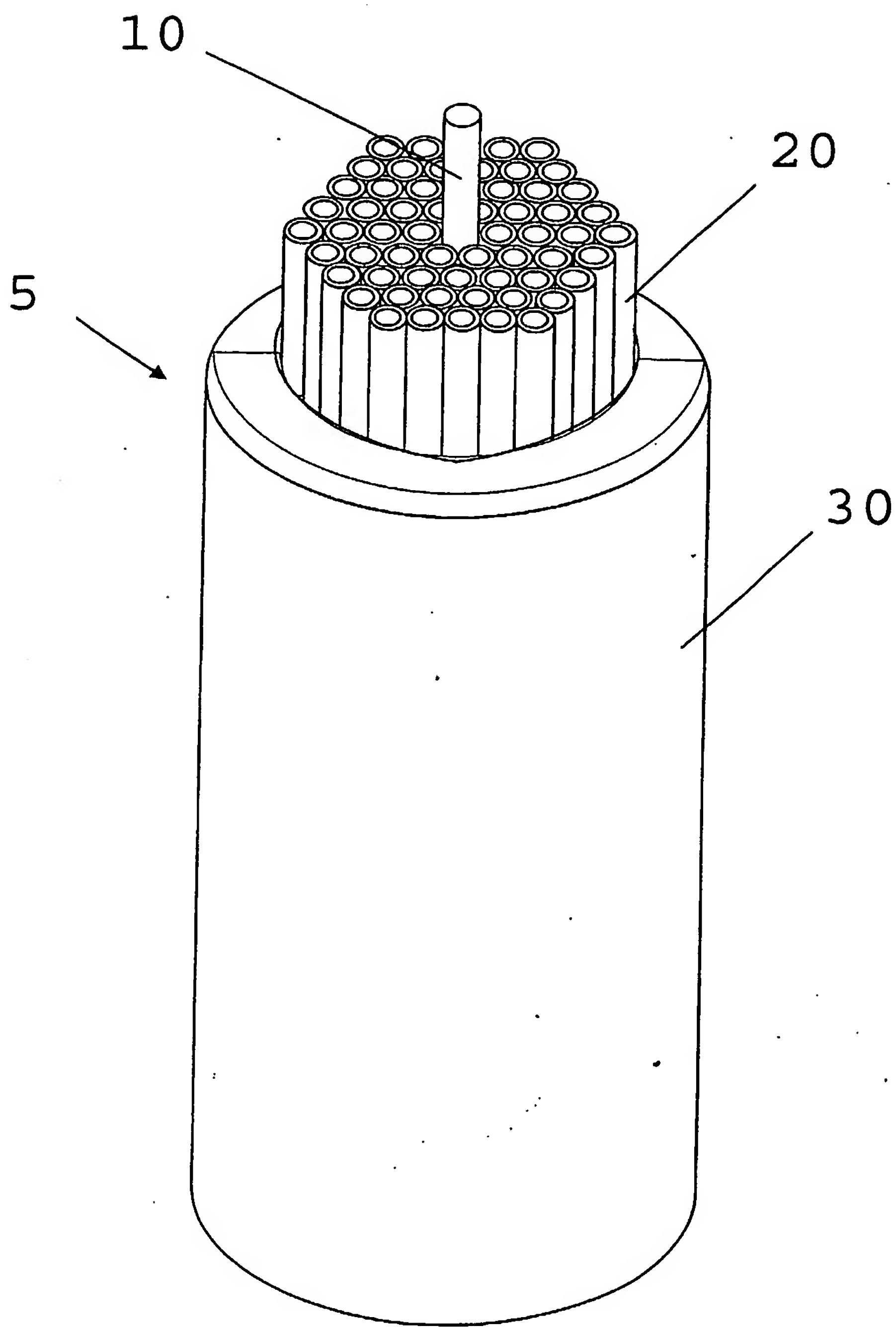


Fig. 2

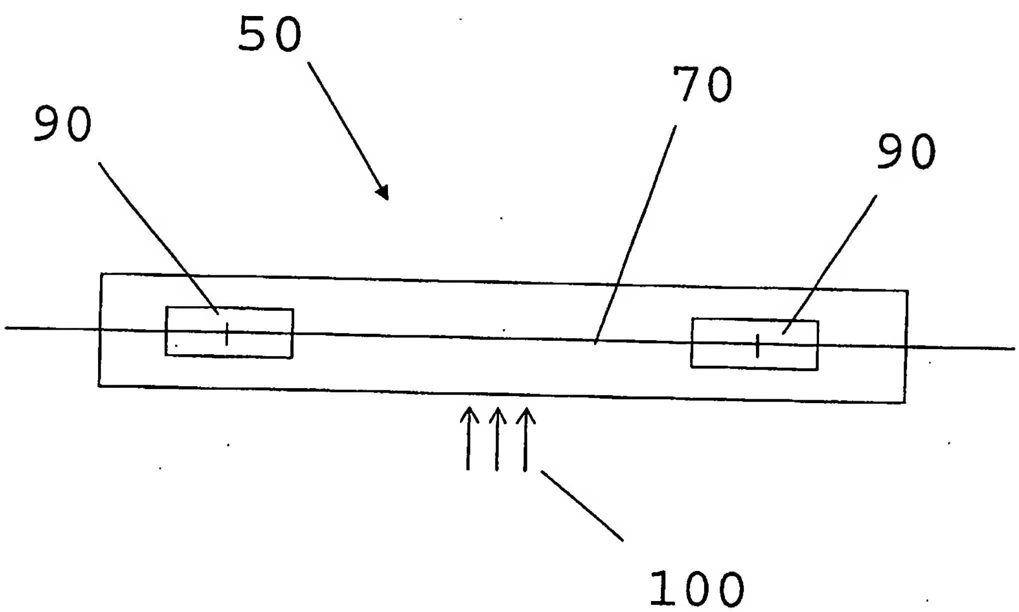
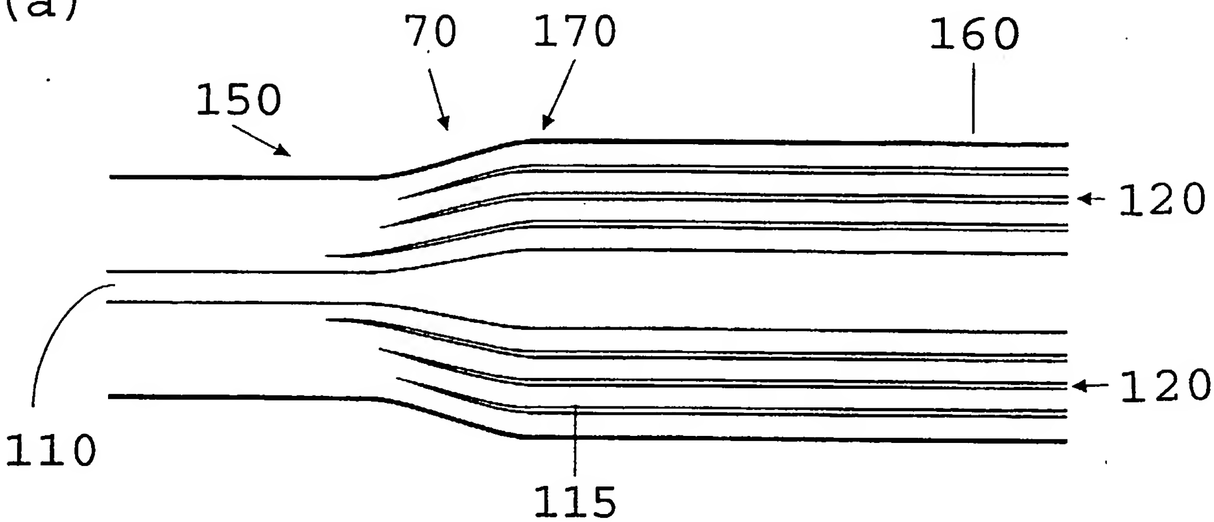
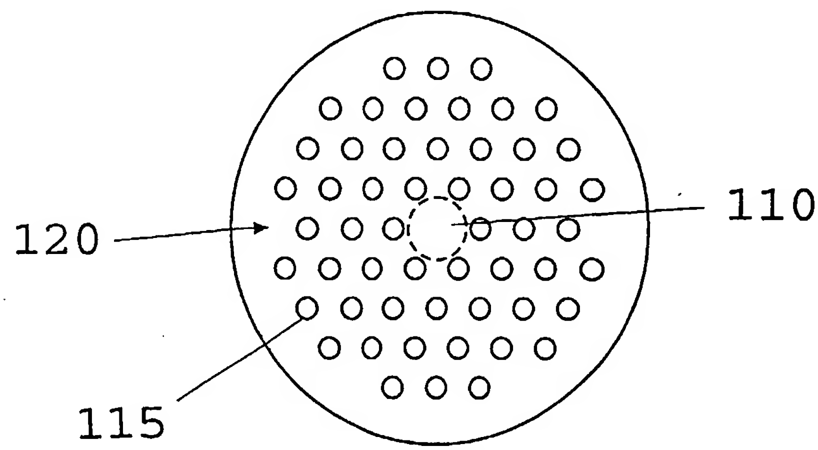


Fig. 3

(a)



(b)



(c)

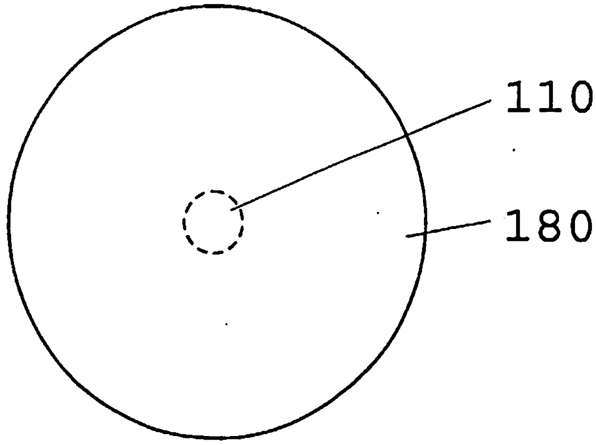


Fig. 4

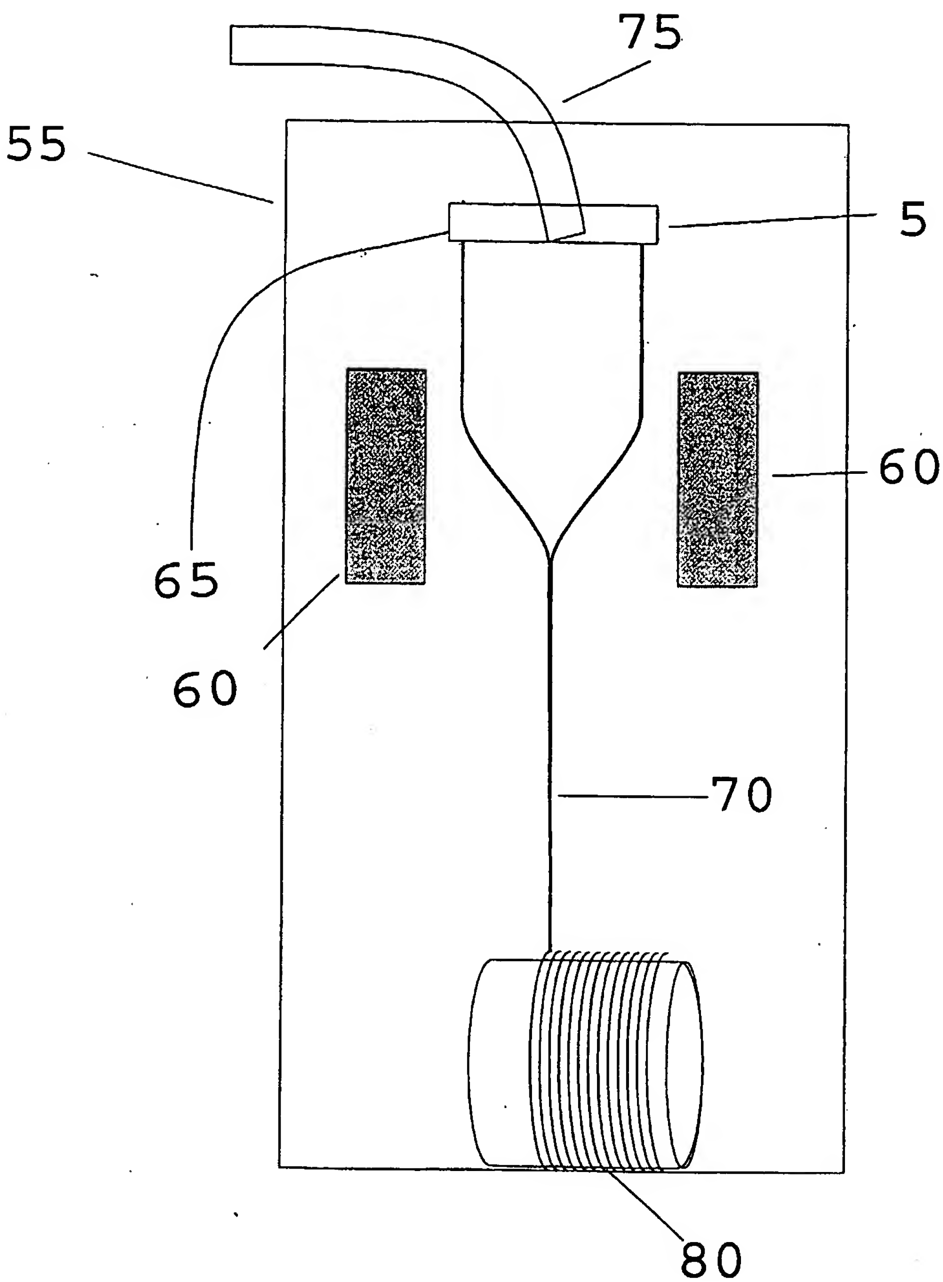


Fig. 5

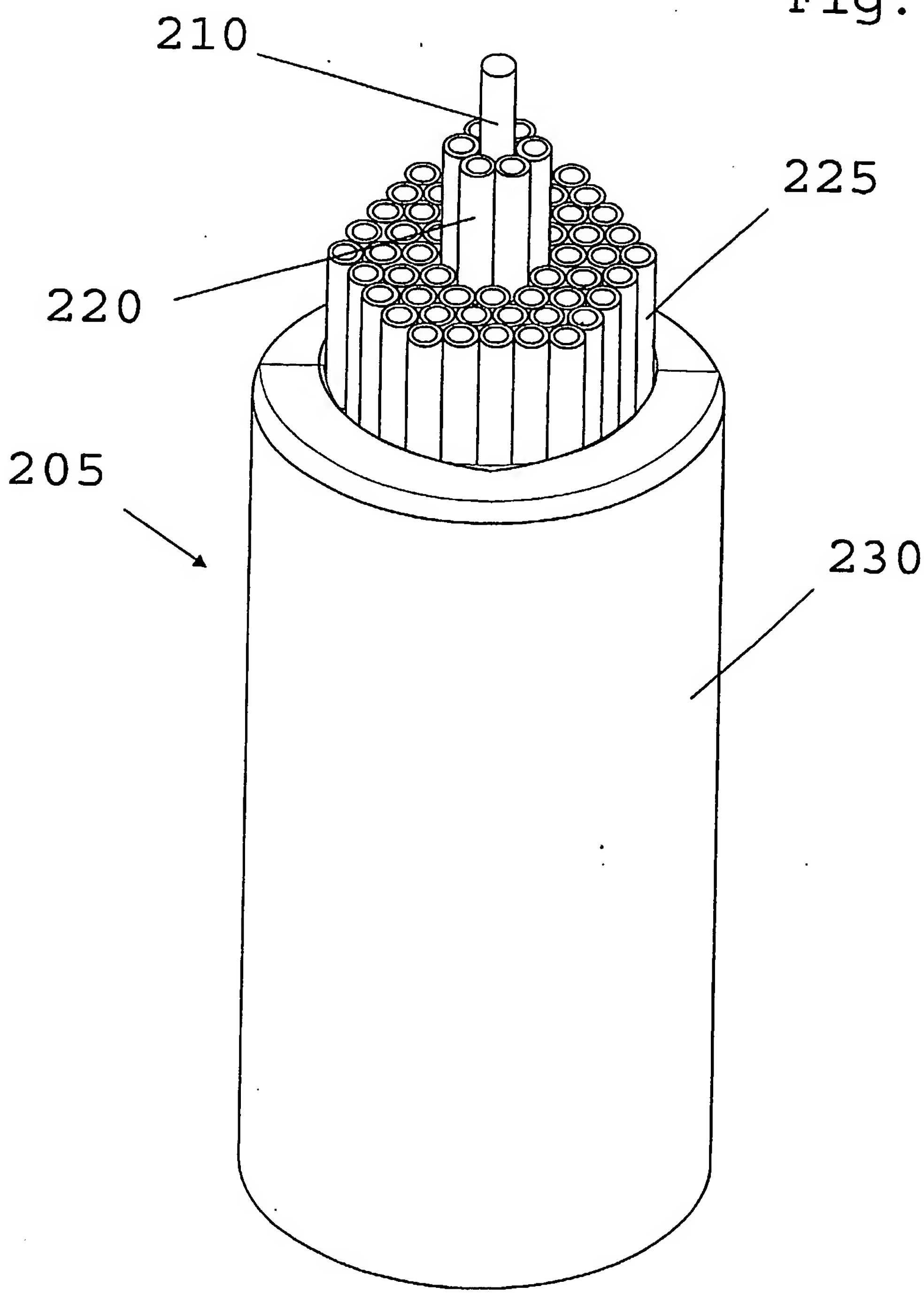


Fig. 6

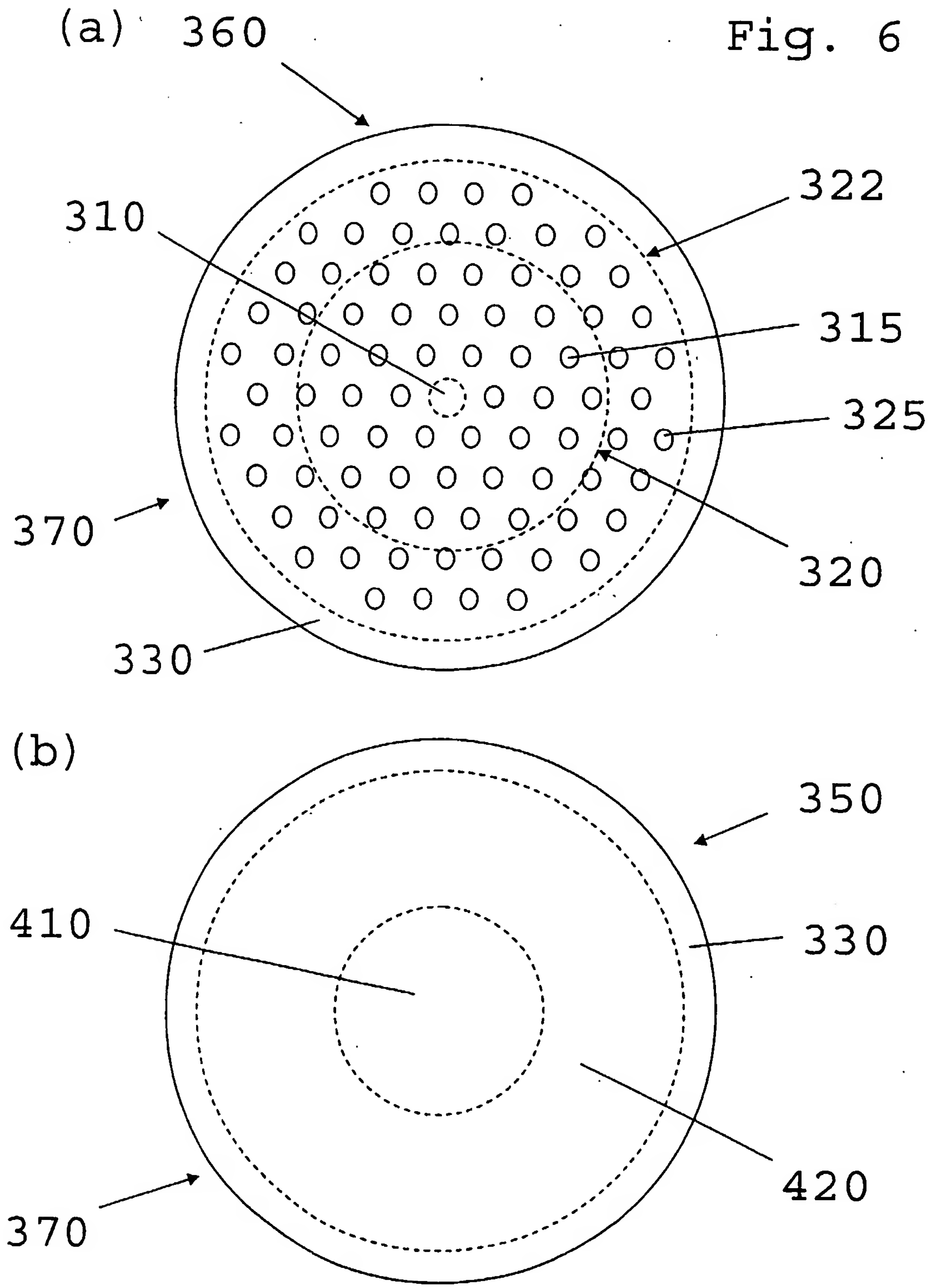


Fig. 7

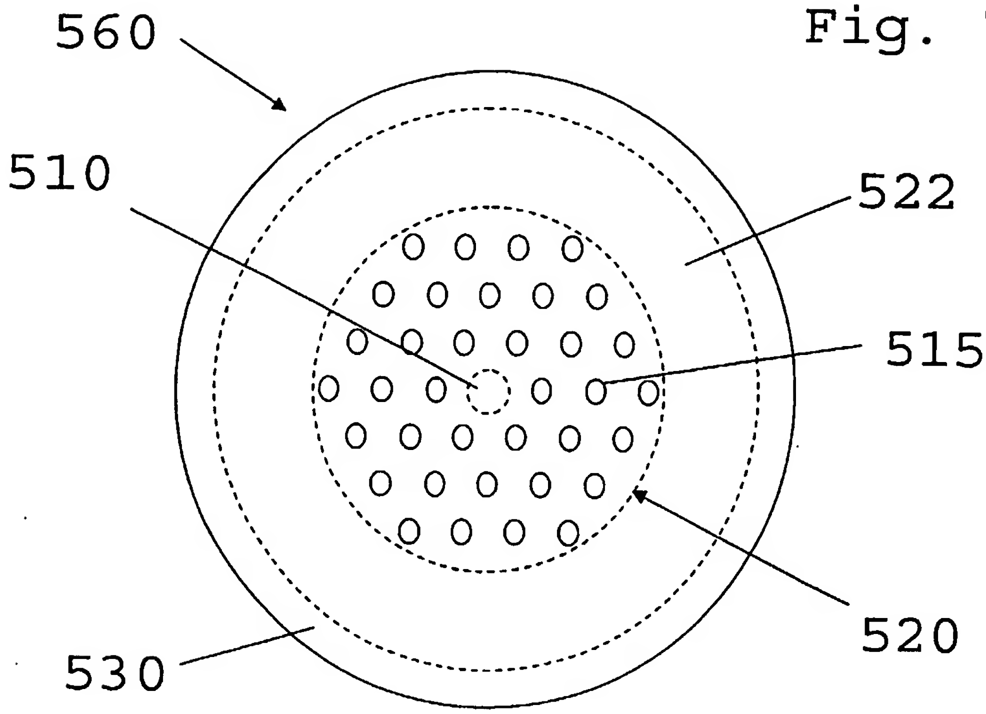


Fig. 8

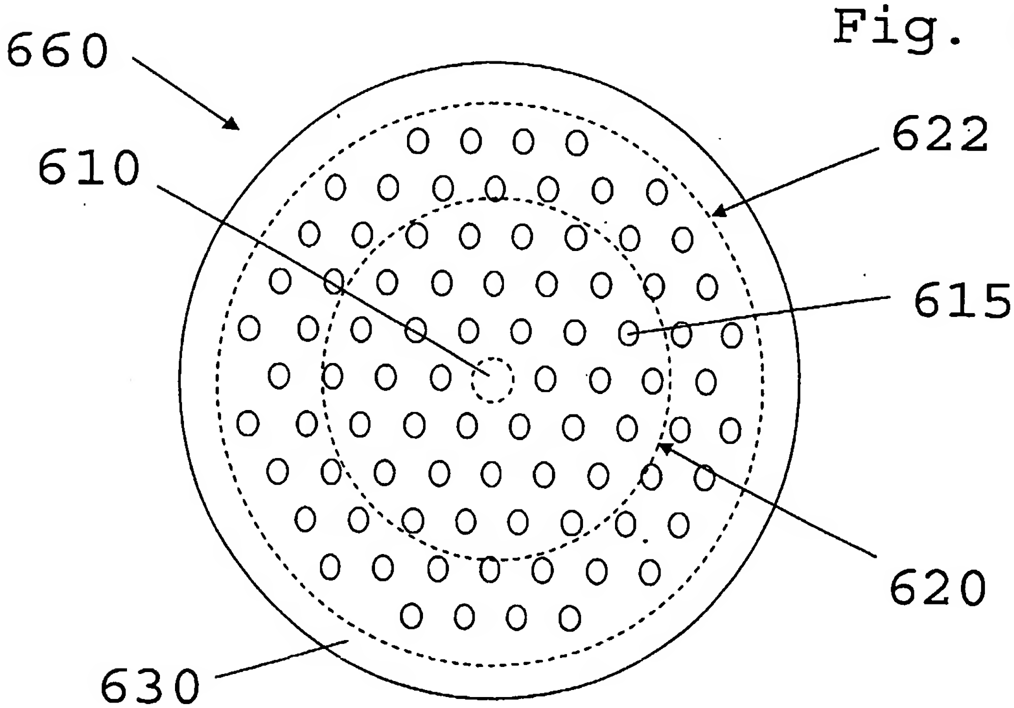
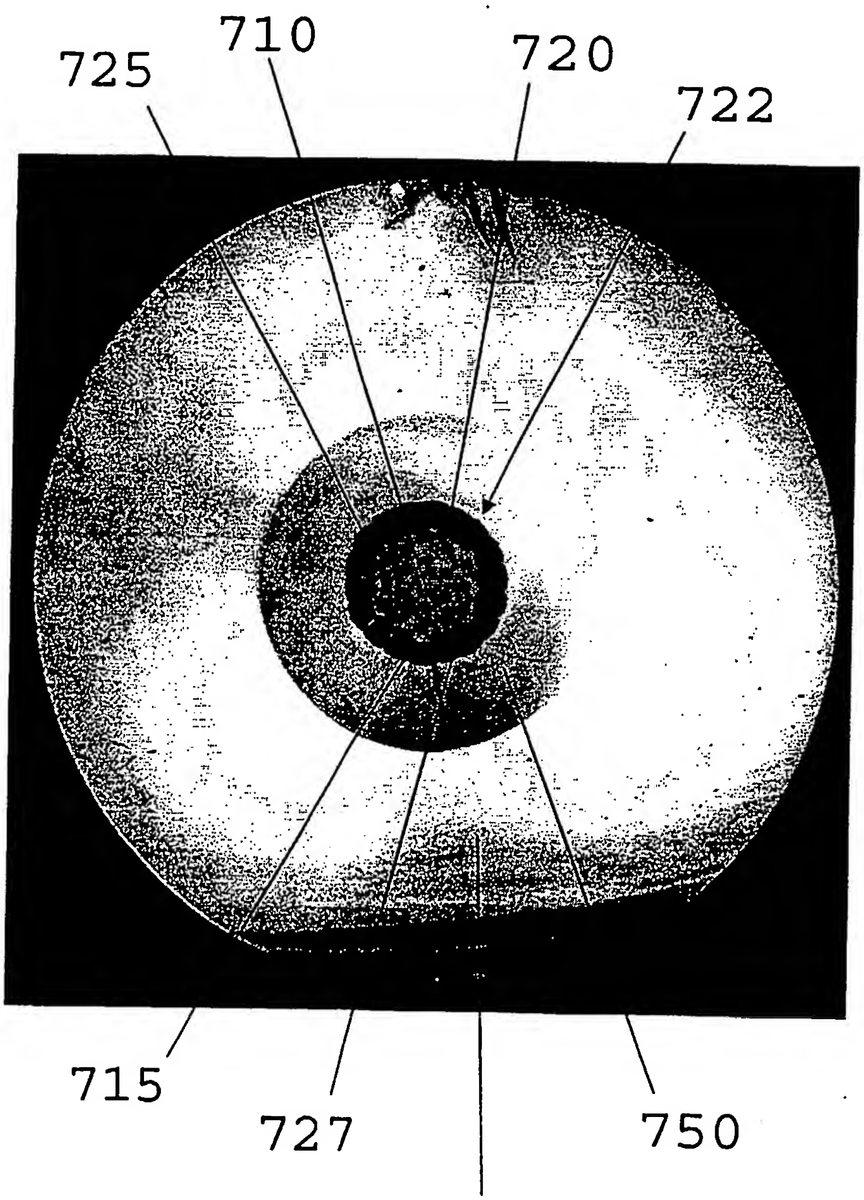


Fig. 9



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A Method and Apparatus Relating to Optical Fibres

This invention relates to the field of optical fibres.

Single-mode and multimode optical fibres are widely used in applications such as telecommunications. Such fibres are typically made entirely from solid materials such as glass, and each fibre typically has the same cross-sectional structure along its length. Transparent material in one part (usually the middle) of the cross-section has a higher refractive index than material in the rest of the cross-section and forms an optical core within which light is guided by total internal reflection. We refer to such a fibre as a conventional fibre or a standard fibre.

Most standard fibres are made from fused silica glass, incorporating a controlled concentration of dopant, and have a circular outer boundary typically of diameter 125 microns. Standard fibres may be single-mode or multimode. Particular standard fibres may have particular properties, such as having more than one core or being polarisation-maintaining or dispersion-compensating.

Standard fibres are in widespread and routine use and a wide range of devices based on standard fibres have been developed. It is therefore advantageous for a new design of optical device for telecommunications applications to be made compatible with pre-existing standard fibre technology.

In the past few years a non-standard type of optical fibre has been demonstrated, called (equivalently) a photonic-crystal fibre (PCF), a holey fibre or a microstructured fibre [J. C. Knight *et al.*, Optics Letters v. 21 p. 203]. Typically, a microstructured fibre is made from a single solid material such as fused silica glass, within which is embedded a plurality of elongate air holes. The holes run parallel to the fibre axis and extend the full length of the fibre. A region of solid material between holes, larger than neighbouring such regions, can act as a

waveguiding fibre core. One way to provide such an enlarged solid region in a fibre with an otherwise periodic array of holes is to omit one or more holes from the structure.

Light can be guided in the core in a manner analogous to total-internal-reflection guiding in standard fibres. However, the array of holes need not be periodic for total-internal-reflection guiding to take place (one may nevertheless refer to such a fibre as a photonic-crystal fibre).

Another mechanism for guiding light in microstructured fibres is based on photonic bandgap effects rather than total internal reflection. For example, light can be confined inside a hollow core (an enlarged air hole) by a suitably-designed array of smaller holes surrounding the core [R. F. Cregan *et al.*, Science v. 285 p. 1537]. True guidance in a hollow core is not possible at all in conventional fibres.

Microstructured fibres can be fabricated by stacking glass elements (rods and tubes) on a macroscopic scale into the required pattern and shape, and holding them in place while fusing them together. This primary preform can then be drawn into a fibre, using the same type of fibre-drawing tower that is used to draw standard fibre from a standard-fibre preform. The primary preform can, for example, be formed from fused silica elements with a diameter of about 0.8 mm.

The microstructured fibre has a number of technologically significant properties, including (not necessarily simultaneously): endlessly single-mode guidance over a very broad range of wavelengths [T. A. Birks *et al.*, Optics Letters v. 22 p. 961], a large mode area to carry high optical powers [J. C. Knight *et al.*, Electronics Letters v. 34 p. 1347], a wide range of dispersion characteristics [A. Ferrando *et al.*, Electronics Letters v. 35 p. 325], high optical nonlinearity [J. K. Ranka *et al.*, Optics Letters v. 25 p. 25], guidance in multiple cores that

may or may not interact [B. J. Mangan *et al.*, Electronics Letters v. 36 p. 1358], and guidance in air or vacuum in a hollow core [R. F. Cregan *et al.*, Science v. 285 p. 1537].

Exploitation of the properties of microstructured fibres would be facilitated by simple and effective means to transfer light between these fibres and standard fibres. In particular, it would be of great benefit to make microstructured fibres directly compatible with existing standard fibre technology. Unfortunately, some of the techniques of conventional fibre optics are not readily applicable to microstructured fibres. For example, an incautious attempt to fusion-splice a microstructured fibre to a standard fibre can cause the air inside the microstructured fibre to expand catastrophically, destroying the joint. In one method of splicing standard fibres, the fibre ends are pushed together and then pulled apart during fusion. Such a method would destroy the holes of a microstructured fibre. If the optical modes of the fibres being joined are not well-matched in size, even a careful joint will be highly lossy.

Tapering techniques involving heat treatment of fibres after they are fabricated can solve some of these problems. International Patent Application No. PCT/GB/00599, published as WO 00/49435, describes how heating and stretching of a microstructured fibre can provide a low-loss transition that transforms the size of the guided mode of the microstructured fibre to match the size of the guided mode of a standard fibre to which coupling is being attempted; however, the match with a standard fibre will be at best approximate.

Alternatively, a special microstructured fibre can be made that has a high-index core that guides light conventionally and is otherwise matched to a standard fibre [J. K. Chandalia *et al.*, IEEE Photonics Technology Letters vol. 13 p. 52]; there are also large air holes in the fibre cladding so that, when the fibre is drawn down, the result

is a microstructured-fibre-like structure. However, the holes in the standard-fibre end of this structure can cause difficulties during fusion-splicing.

Takemi Hasegawa et al., OFC 2001 Post-deadline paper PD5-1 (2001) and ECOC'01 Proceedings pp 324-325 We.L.2.5 (2001) describe a "Hole-assisted lightguide fiber" (HALF) structure. The described fibre guides light by total internal reflection at the interface between a pure silica core and a Fluorine-doped silica cladding (as in a typical standard fibre). However, the fibre also includes four holes outside the pure silica core region. The holes are provided to depress the effective refractive index of a region of the cladding in order to provide a "W-shaped" refractive index profile, of a type well known in standard fibre technology, which provides desirable dispersion properties in the fibre. The holes in this fibre do not function to confine light to the core region (indeed, that is deliberately avoided in order to reduce losses in the fibre); rather, confinement is achieved by the refractive index step.

An object of the invention is to provide a method of facilitating the exploitation of standard-fibre technology in devices incorporating photonic crystal fibres.

According to the invention there is provided a method of manufacturing an optical fibre, the method comprising:

(a) providing an elongate element comprising (i) a core region, (ii) a cladding region that surrounds the core region and that includes a plurality of elongate holes, (iii) a higher-index zone that comprises dielectric material having a first, higher bulk refractive index and (iv) a lower-index zone that surrounds the higher-index zone and comprises dielectric material having a second, lower bulk refractive index.

(b) at least partially collapsing the holes in a length of the element to provide a collapsed portion comprising a core region, formed from the higher-index zone of the

elongate element, and a cladding region, formed from the lower-index zone of the elongate element, such that the core region in the collapsed portion has a refractive index that is higher than the refractive index of the cladding region in the collapsed portion.

The core region in the elongate element may include a plurality of elongate holes.

Preferably, the holes in the collapsed portion are completely collapsed, such that the core region and the cladding region in the collapsed portion are solid and form a standard-fibre portion.

Any suitable dielectric material may be used to make the fibre, for example a glass or a polymer. Any suitable dopant(s) may be used to change bulk material refractive index (it will be understood that references to 'bulk' refractive index are to the refractive index of a region of solid material excluding the effects of any microstructure, i.e. as opposed to the 'effective' refractive index). For example, Germanium-doped Silica has a higher refractive index than undoped silica, which in turn has a higher refractive index than Fluorine-doped Silica.

Preferably, the cladding region of the elongate element comprises a first cladding region, comprising a plurality of elongate holes, and a second cladding region. Preferably, the second cladding region is solid. Alternatively, the second cladding region also comprises a plurality of elongate holes.

Preferably, the higher-index zone comprises the core region and the first cladding region of the elongate element, such that those regions form the core region of the collapsed portion and the lower-index zone comprises the second cladding region of the elongate element, such that it forms the cladding region of the collapsed portion. Thus the standard-fibre portion may have a larger diameter core than the microstructured-fibre portion. Thus, for example, the core and first cladding region of the microstructured

fibre may be of undoped silica and the second cladding region may be of Fluorine-doped Silica. Collapse of the holes will then result in the standard-fibre portion having a core of undoped Silica and a cladding of Fluorine-doped Silica.

Preferably, the cladding region of the elongate element includes a further cladding region which surrounds the second cladding region, and the lower-index zone also comprises the further cladding region, such that the second cladding region and the further cladding region form the cladding region of the collapsed portion. Such a further region may provide improved mode confinement. Of course, regions of an optical fibre that are sufficiently far from the core that substantially no light reaches them may be of any refractive index.

A problem with forming the core region from the first cladding regions and the core region of the elongate element is that the collapse of the holes in the first cladding region can result in refractive index effects that cause the fibre to fail to guide in a length of the fibre within a transition portion between the standard-fibre portion and the microstructured-fibre portion. The size of the holes in the transition portion will, of course, vary from their largest size in the microstructured fibre portion to zero in the fully collapsed standard-fibre portion. As the holes collapse, the field spreads. Loss can happen as the mode spreads out of the core region of the microstructured portion if the effective refractive index step between the first and second outer cladding regions is not sufficiently high. If it spreads as far as the second cladding region before the mode index rises above that region's index, the light will leak. This effect may be avoided or ameliorated if the holes in the second cladding region are larger than the holes in the first cladding region.

Alternatively, the second cladding region may be arranged sufficiently far away from the core region for light substantially not to reach it.

Alternatively, holes may be provided all the way out to the edge of the cladding region.

Another alternative solution is for the region forming the second cladding region of the collapsed fibre to have a sufficiently low material refractive index that the mode index of the guided mode in the core never falls below it.

In an alternative arrangement, the higher-index zone comprises the core region of the elongate element, such that that core region forms the core region of the collapsed portion, and the lower-index zone of the elongate element comprises the cladding region of the elongate element, such that that cladding region forms the cladding region of the collapsed portion.

Preferably, the elongate element is a microstructured optical fibre and the collapsed portion is a standard-fibre portion. It will be understood that the term "microstructured optical fibre" refers to an optical fibre or a length of optical fibre in which guidance of light involves physical effects (such as effective-index total-internal-reflection guidance or photonic-bandgap guidance) that result from the presence of the plurality of elongate holes. It will be understood that the term "standard fibre" refers to an optical fibre or a length of optical fibre in which guidance of light results from total-internal-reflection at the interface (which may, of course, be distributed) between a solid core and a solid cladding. In such post-fabrication treatment of a microstructured optical fibre, the holes may be collapsed by heating the fibre, for example, using a flame or a laser, or by pulling the fibre through the furnace of a fibre-drawing tower and varying the temperature of the furnace. The fibre may be stretched during heating, for example on a standard fibre-tapering rig.

Alternatively, the elongate element is a preform for a microstructured fibre and the collapsing is carried out during drawing of the preform into the fibre, so that the collapsed portion forms a standard-fibre portion in the drawn fibre. Hole collapse may thus be achieved during the initial fabrication of the fibre from a preform, rather than post-fabrication. Preferably, at least some of the holes are pressurised during drawing. Preferably, at least some of the holes are evacuated during drawing to cause the collapse of the holes in the standard portion of the elongate element. Preferably, the preform is formed by stacking a plurality of elements. Preferably, at least some of the elements are glass tubes and/or rods. More preferably, all of the elements are glass tubes and/or rods. At least one of the elements may itself be formed from a plurality of glass tubes and/or rods. Preferably, the elements have a substantially circular outer cross-section. More preferably the elements have substantially the same outer diameter. Preferably, the elements are fused together. Preferably, the stack is assembled on a larger scale and then drawn down in size to form the desired preform.

Alternatively, the preform element may be formed by extrusion. Alternatively, the preform element may be formed by casting of sol-gel material.

Preferably, the preform element is enclosed in an outer jacket.

Preferably, further processing of the standard-fibre portion is carried out in order to provide a standard-fibre device comprising the standard-fibre portion. The term "standard-fibre device" refers to any device that has been implemented using standard fibres. It is a particular advantage of the invention that well-known standard-fibre devices may be integrated into a microstructured fibre; it is in many cases difficult to implement such devices directly into microstructured fibres. For example, a

grating may be written onto the core of the standard-fibre portion. If it were attempted to write a grating onto the core of a microstructured fibre, it is likely that complications would arise resulting from scattering, from the holes, of the ultra-violet light used to write the grating. To give another example, the fibre may be cleaved in the standard fibre portion and a further standard fibre may be spliced to the cleaved portion. Thus a microstructured fibre may be joined to a standard fibre without any of the problems associated with direct splicing of holey structures. To give yet another example, a further standard fibre may be fused to the standard-fibre portion to provide a fibre coupler at the standard-fibre portion. The microstructured fibre may thus be joined by splicing or coupling to a standard-fibre device such as a fibre amplifier. Of course, two microstructured fibres may be spliced or fused to each other by providing each with a standard-fibre portion.

Also according to the invention there is provided an optical fibre comprising: a microstructured fibre portion comprising (i) a core region, (ii) a cladding region that includes a plurality of elongate holes, (iii) a higher-index zone that comprises dielectric material having a first, higher bulk refractive index and (iv) a lower-index zone that surrounds the higher-index zone and comprises dielectric material having a second, lower bulk refractive index; and a collapsed fibre portion comprising a core region formed from the higher-index zone and a cladding region formed from the lower-index zone, such that the core region in the collapsed portion has a refractive index that is higher than the refractive index of the cladding region in the collapsed portion.

Preferably, the holes have fully collapsed in the collapsed fibre portion such that it forms a standard-fibre portion.

Preferably, the fibre, in which the holes have fully collapsed to form a standard-fibre portion, further comprises a transition fibre portion connecting the microstructured-fibre portion to the standard-fibre portion, comprising a core region and a plurality of elongate holes that each has a cross-sectional diameter that reduces along the transition portion and is zero at the standard fibre portion, wherein the transition fibre portion enables light to pass adiabatically from the microstructured-fibre portion to the standard-fibre portion. The criterion for adiabaticity (described to various approximations in J. D. Love *et al.*, Electronic Letters vol. 22 p. 912 and J. D. Love *et al.*, IEEE Proceedings J vol. 138 p. 343) defines the maximum rate of change of a waveguide transition, along the length of the waveguide, that preserves low-loss propagation; that maximum can be calculated using numerical techniques well-known to those skilled in the art. The transition portion may therefore be a low-loss interface between the microstructure-fibre portion and the standard-fibre portion.

Preferably, the cladding region of the microstructured-fibre portion comprises a first cladding region comprising a plurality of elongate holes, and a second cladding region. Preferably, the second cladding region is solid. Alternatively, the second cladding region comprises a plurality of elongate holes.

Preferably, the first cladding region, the core region of the microstructured-fibre portion and the core region of the collapsed-fibre portion all have a higher bulk refractive index than the bulk refractive index of the second cladding region (in the case, for example, of the first cladding region, the bulk refractive index is the refractive index of the material surrounding the holes). More preferably, each of those regions has the same refractive index. Still more preferably, each of those regions is made of the same material.

Alternatively, the core region of the microstructured-fibre portion and the core region of the collapsed-fibre portion each have a higher bulk refractive index than the bulk refractive index of the first and second cladding regions. More preferably, each of those regions has the same refractive index. More preferably, each of those regions is made of the same material.

The cladding region of the microstructured portion may include a further cladding region, which surrounds the second cladding region.

Preferably, the collapsed-fibre portion is comprised in a standard-fibre device, such as those discussed above.

Preferably, the plurality of elongate holes are arranged in a periodic pattern. More preferably, the fibre can guide light because the periodic pattern of holes results in photonic band gap.

The microstructured fibre portion may be arranged to have any of several useful properties; for example, it may be a single mode fibre, an endlessly single-mode fibre, a multiple core fibre, a dispersion modified fibre, a large mode area fibre or a highly nonlinear fibre. If the fibre is multimode in the microstructured-fibre portion, provision of an adiabatic transition between the microstructured-fibre portion and the collapsed-fibre portion may be used to ensure that an optical mode in a single mode of the collapsed-fibre portion remains single mode in the microstructured fibre portion and/or that an optical mode in a single mode of the microstructured-fibre portion remains single-mode in the collapsed-fibre portion.

The fibre may have a standard-fibre portion at each end, formed by fully collapsing the holes. The fibre may then be supplied as a "black box", with users able to treat it as a length of standard fibre, in that its entrance and exit interfaces may be accessed as with a standard fibre. Providing a standard-fibre portion at each end of a microstructured fibre also has the advantage of sealing the

elongate holes, so that contaminants such as moisture may not enter.

Of course, the optical device may have other features corresponding to features described above with reference to the method according to the invention.

Also according to the invention there is provided a method of transferring light from a microstructured fibre to a standard fibre, the method comprising the step of propagating the light along a fibre described above as according to the invention. Of course, the microstructured fibre and/or the standard fibre may be portions of the same fibre.

Also according to the invention there is provided a microstructured optical fibre comprising an inner region of material having a first, higher bulk refractive index and an outer region of a material having a second, lower bulk refractive index, the fibre also comprising a plurality of elongate holes that provide the predominant guiding mechanism in the fibre, such that, in use, the holes influence propagation in the fibre to the extent that collapse of the holes would cause the spot size of a mode guided at a wavelength of operation to change by more than 20%.

Preferably, the effect on spot size would be larger; for example, preferably collapse of the holes would cause the spot size to change by more than 50% or more than 100%.

In fibres according to the invention, the elongate holes provide, in longitudinal regions where they are present, stronger guidance of propagating light than the step in material refractive index provides.

The bulk refractive indices (i.e. the refractive indices of the material, excluding the holes) are such that collapsing the holes would result in a standard fibre. Preferably, the holes are collapsed by heat treatment.

Also according to the invention, there is provided a microstructured fibre for supporting a guided mode, the

fibre comprising an inner region comprising material having a first, higher bulk refractive index, and a region, surrounding the inner region, having a second, lower bulk refractive index and comprising a plurality of elongate holes that provide the predominant guidance mechanism in the fibre, such that, in use, more than 90% of the power of the guided mode propagates at a wavelength of operation, within the inner region.

Preferably, more power is guided in the inner region; for example, preferably more than 95%, 98% or even 99% of the power of the guided mode propagates in the inner region.

Also according to the invention there is provided a microstructured fibre comprising (i) a core region, (ii) a cladding region including a plurality of elongate holes, (iii) a higher-index zone that comprises dielectric material having a first, higher bulk refractive index and (iv) a lower-index zone that surrounds the higher-index zone and comprises dielectric material having a second, lower bulk refractive index, characterised in that the holes are arranged to confine light to the core region of the fibre.

Embodiments of the invention will now be described, by way of example only, with reference to the drawings, of which:

Fig. 1 is a preform for drawing into a microstructured fibre;

Fig. 2 is a microstructured fibre being heated and stretched to produce a collapsed region, in a method according to the invention;

Fig. 3 is: (a) a longitudinal cross-sectional view of the optical fibre of Fig. 3; (b) a transverse cross-sectional view of that fibre in the microstructured-fibre portion of its length; and (c) a transverse cross-sectional view of that fibre in the standard-fibre portion of its length.

Fig. 4 is the preform of Fig. 1 being drawn into a fibre;

Fig. 5 is a second preform for drawing into a microstructured fibre.

Fig 6. is: (a) a cross-sectional view of a fibre drawn from the preform of Fig. 5 in the microstructured portion of its length; and (b) a cross-sectional view of that fibre in the standard-fibre portion of its length.

Figs. 7 and 8 are cross-sectional views of further fibres according to the invention in their microstructured portions.

Fig. 9 is a micrograph of a further fibre according to the invention.

In a first embodiment of the invention, a microstructured fibre 70 is drawn from a preform 5 (Fig. 1). The preform comprises a central, silica core 10, of diameter 1mm and is surrounded by a bundle of silica tubes 20, of external diameter 1mm and internal diameter 0.45mm, which are doped with Fluorine to lower their refractive index. The tubes 20 are arranged in a triangular lattice pattern. A jacket 30 is provided to hold the bundle 5 together and to provide a protective outer region for fibre 70.

Bundle 5 is drawn into fibre 70 on drawing rig 55 (Fig. 4). Drawing rig 55 is of the type typically used to draw a standard fibre from a preform. Preform 5 is held so that its lower parts are within furnace 60. Fibre 70 is gradually pulled from the heated parts of preform 5 in the manner well known in the art. Once a sufficient length has been drawn, drawing continues by the action of rotating drum 80, around which fibre 70 is wound.

After fibre 70 is drawn, it comprises, in transverse cross-section (Fig. 3 (b)) a central, undoped silica core region 110 surrounded by cladding region 120. Tubes 20 have fused together during the drawing of the fibre to form cladding region 120. The central holes of the tubes 20 form elongate holes 115 in the drawn fibre. The triangular lattice pattern of the tubes 20 of preform 5 is retained in

the pattern of the holes 115 in the cladding region 120. Holes 115 have a pitch of 3 microns.

The matrix material of cladding region 120 is Fluorine-doped Silica, because that is the material of tubes 20 from which it is derived. Fluorine-doped Silica has a lower refractive index than undoped silica, and the effective refractive index is lowered still further by the presence of holes 115 (the exact volume of the effective refractive index of the cladding depends upon the nature of a mode guided therein, but it can be calculated by a person skilled in the art and will in general be between the refractive index of the holes and the refractive index of the matrix glass). Hence the fibre 70 will confine and guide light in its core 110 by total internal reflection from the cladding region 120.

After the fibre 70 has been drawn, it is placed in a fibre-tapering rig 50 of the type generally used to taper standard fibres (Fig. 2). The fibre 70 is clamped to translation stages 90 and a region of the fibre of length about 10cm is heated using a burner flame 100 so that holes 115 collapse in that region. The fibre is then cleaved in the region in which the holes have collapsed. The fibre 70 now comprises (Fig. 3 (a)) a microstructured-fibre portion 160 that has not been heated and has the transverse cross-section shown in Fig. 3(b), a standard-fibre portion 150, in which holes 115 have completely collapsed and a transition region 170, between lengths 150 and 160, in which holes 115 become progressively smaller. Transition region 170 is formed by exposing fibre 70 to flame 100 for a progressively shorter time (and/or at a progressively lower temperature) as untreated region 160 is approached. It is of length 20cm in order to ensure that the transition in hole size is sufficiently gradual for the condition for adiabaticity to be met, i.e., for passage of light through the transition region to be lossless. We have noted that the loss properties of regions containing tapered holes are

particularly sensitive when the holes are small and therefore particular care has to be taken to make the transition sufficiently gradual near the region of the complete collapse.

In the standard-fibre portion 150, the fibre 70 has a cross section as shown in Fig. 3(c). Core region 110 is of undoped silica and cladding region 180 is of Fluorine-doped Silica, and so the fibre 70 also confines light to the core region 110 in length 150 by total internal reflection, as in length 160. However, there are no holes in standard-fibre region 150 and so that region 150 may readily be spliced to a standard fibre to form a very low loss join, without the problems associated with holes.

In an alternative embodiment (Fig. 4), fibre 70 is again drawn from preform 5 on rig 55, but in this embodiment cap 65 is sealed to jacket 30 of the preform 5. Cap 65 is connected via tube 75 to a source of pressurised air (cap 65 and tube 75 are shown in dotted lines). The pressurised air helps prevent collapse of holes 115 and standard fibre region 150 is formed by disconnecting the pressurised air from cap 65 when region 180 is in furnace 60.

Of course, the combination of a core region of undoped silica and a cladding region of Fluorine-doped silica can be exchanged for a core region of Germanium-doped silica and a cladding region of undoped silica, or for any other suitable combination of materials providing a higher-index core and lower-index cladding.

An alternative preform 205 (Fig. 5) for use in the invention comprises a central, solid core 210 of Germanium-doped Silica, an inner ring of smaller tubes 220 of inner diameter 0.5 mm and outer diameter 1 mm of Germanium-doped Silica, an outer ring of larger tubes 225 of undoped silica of inner diameter 0.7 mm and outer diameter 1 mm, and a silica jacket 230. The microstructured fibre 370 (Fig. 6) drawn from preform 205 (in the manner described above) comprises a central core 310, derived from core 210, an

inner cladding region 320 derived from inner tubes 220, an outer cladding region 322 derived from outer tubes 225 and jacket region 330 derived from jacket 230. Core 310 is of Germanium-doped Silica. Inner cladding region 320 is also of Germanium-doped Silica, but acts as a cladding region because holes 315, resulting from the holes of tubes 220, lower its effective refractive index. Holes 315 are of diameter 1 micron and pitch 2 microns. There is therefore a refractive index step between the core and the inner cladding, such that total internal reflection can occur. Outer cladding region 322 is of undoped silica. Its holes 325, derived from the holes of tubes 225, are of diameter 1.4 microns and pitch 2 microns. Outer cladding region 322 has a lower effective refractive index than inner cladding region 320 and core region 310, because of the lower refractive index of undoped silica and the larger air holes 325.

As with fibre 70 in the earlier example, fibre 370 is heat-treated on a fibre-tapering rig to create standard-fibre length 350. In that region of the fibre, holes 315 and 325 have collapsed. The remaining material forms essentially a length of standard fibre, having a central guiding core 410 of Germanium-doped Silica and a cladding region 420 of undoped silica. Core 410 is formed from core region 310 and inner cladding region 320 in the untreated fibre. Cladding region 420 is formed from outer cladding region 322. Again, most of the rest of the fibre 370 remains microstructured-fibre 360, apart from a transition region (not illustrated) to standard-fibre region 350. The fibre can be cleaved in region 350 to provide a standard-fibre termination that is readily joined to other standard fibres or standard-fibre portions. Holes 325 are larger than holes 315 in order to ensure that, during hole collapse under heat treatment, the outer holes 325 collapse after the inner holes 325, ensuring that there is at all points in the

transition region a refractive index step that confines light within the fibre 370.

Further embodiments of the invention are shown in Figs. 7 and 8.

Fig. 7 represents two embodiments. In both embodiments, the microstructured portion 560 of the fibre comprises a core region 510, an inner cladding region 520, comprising bulk silica in which a plurality of elongate holes 515 are embedded in a solid silica outer cladding region 522 and a jacket 530. In both embodiments core 510 is undoped silica and outer cladding region 522 is Fluorine-doped silica. However, in the first embodiment, the inner cladding region 520 is pure silica, whereas in the second embodiment, the inner core region 520 is Fluorine-doped silica. Thus, when holes 515 are collapsed to form a standard-fibre portion (not shown), in the first embodiment the material of inner cladding region 520 forms part of the undoped silica core of the standard fibre and in the second embodiment inner cladding region 520 forms part of the Fluorine-doped cladding of the standard fibre.

Fig. 8 represents a further embodiment which is similar to that of Fig. 5. Microstructured portion 660 of the fibre comprises a core 610 of Germanium-doped silica, an inner cladding region 620 of Germanium-doped silica and an outer cladding region 622 and a jacket 630, each of undoped silica. Both cladding regions 620, 622 comprise a plurality of elongate holes 615. In contrast to the fibre of Fig. 5, all holes 615 are of the same cross-sectional diameter. When holes 615 are collapsed to form a standard-fibre portion (not shown), a (germanium-doped) core of that standard-fibre portion results from core 610 and inner cladding region 620. The (undoped) cladding region of the standard-fibre portion results from outer cladding region 622.

In the fibre of Fig. 5, mode-guidance during hole collapse and in the transition region is maintained by the

use of larger holes to provide a lower effective refractive index in the outer cladding region. In the fibre of Fig. 8, mode-guidance is maintained by using a high Germanium doping level to provide a large refractive index difference between the inner and outer cladding regions.

Fig. 9 is a micrograph of an example of a fibre fabricated according to the invention. The fibre comprises a core 710, an inner cladding region 720, comprising two concentric rings of holes 715, arranged on a triangular lattice, outer cladding region 722, comprising a single ring of holes 725, which are arranged on the same triangular lattice but are considerably larger than holes 715 (holes 725 being separated from each other only by thin webs of silica 727), further cladding region 750, which is solid silica and jacket 730 (which is of undoped silica). Core 710 and inner cladding region 720 are of undoped silica. Outer cladding region 722 and further cladding region 750 are of silica doped with Fluorine. Thus, in the collapsed, standard-fibre portion of the fibre (not shown), core 710 and inner cladding region 720 form an undoped silica core and outer cladding region 722 and further cladding region 750 form a Fluorine-doped cladding region. Provision of solid, Fluorine-doped further cladding region 750 provides improved confinement of light modes to the fibre core, in both the microstructured-fibre portion and the standard-fibre portion of the fibre.

Claims

1. A method of manufacturing an optical fibre, the method comprising:

(a) providing an elongate element comprising (i) a core region, (ii) a cladding region that surrounds the core region and that includes a plurality of elongate holes, (iii) a higher-index zone that comprises dielectric material having a first, higher refractive index and (iv) a lower-index zone that surrounds the higher-index zone and comprises dielectric material having a second, lower refractive index.

(b) at least partially collapsing the holes in a length of the element to provide a collapsed portion comprising a core region, formed from the higher-index zone of the elongate element, and a cladding region, formed from the lower-index zone of the elongate element, such that the core region in the collapsed portion has a refractive index that is higher than the refractive index of the cladding region in the collapsed portion.

2. A method as claimed in claim 1, in which the holes in the collapsed portion are completely collapsed, such that the core region and the cladding region in the collapsed portion are solid and form a standard fibre portion.

3. A method as claimed in claim 1 or claim 2, in which the cladding region of the elongate element comprises a first cladding region, comprising a plurality of elongate holes, and a second cladding region that substantially surrounds the first cladding region.

4. A method as claimed in claim 3, in which the second cladding region is solid.

5. A method as claimed in claim 3, in which the second cladding region comprises a plurality of elongate holes.

6. A method as claimed in any of claims 3 to 5, in which the higher-index zone comprises the core region and the first cladding region of the elongate element, such that

they form the core region of the collapsed portion and the lower-index zone comprises the second cladding region of the elongate element, such that it forms the cladding region of the collapsed portion.

7. A method as claimed in claim 6, in which the cladding region of the elongate element includes a further cladding region which surrounds the second cladding region, and the lower-index zone also comprises the further cladding region, such that the second cladding region and the further cladding region form the cladding region of the collapsed portion.

8. A method as claimed in any of claims 3 to 5, in which the higher-index zone comprises the core region of the elongate element, such that that core region forms the core region of the collapsed portion, and the lower-index zone of the elongate element comprises the cladding region of the elongate element, such that that cladding region forms the cladding region of the collapsed portion.

9. A method as claimed in any of claims 1 to 8, in which the elongate element is a microstructured optical fibre and the collapsed portion is a standard-fibre portion.

10. A method as claimed in any of claims 1 to 8, in which the elongate element is a preform for a microstructured fibre and the collapsing is carried out during drawing of the preform into the fibre, so that the collapsed portion forms a standard-fibre portion in the drawn fibre.

11. A method as claimed in claim 10, in which at least some of the holes are pressurised during drawing.

12. A method as claimed in claim 10 or claim 11, in which at least some of the holes are evacuated during drawing to cause the collapse of the holes in the standard portion of the elongate element.

13. A method as claimed in any preceding claim, in which further processing of the standard-fibre portion is carried out in order to provide a standard-fibre device comprising the standard-fibre portion.

14. An optical fibre comprising: a microstructured fibre portion comprising (i) a core region, (ii) a cladding region that includes a plurality of elongate holes, (iii) a higher-index zone that comprises dielectric material having a first, higher bulk refractive index and (iv) a lower-index zone that surrounds the higher-index zone and comprises dielectric material having a second, lower bulk refractive index; and a collapsed fibre portion comprising a core region formed from the higher-index zone and a cladding region formed from the lower-index zone, such that the core region in the collapsed portion has a refractive index that is higher than the refractive index of the cladding region in the collapsed portion.

15. A fibre as claimed in claim 14, in which the holes have fully collapsed to form a standard fibre portion.

16. A fibre as claimed in claim 15, the fibre further comprising a transition fibre portion connecting the microstructured-fibre portion to the standard-fibre portion, comprising a core region and a plurality of elongate holes that each has a cross-sectional diameter that reduces along the transition portion and is zero at the standard fibre portion, wherein the transition fibre portion enables light to pass adiabatically from the microstructured-fibre portion to the standard-fibre portion.

17. A fibre as claimed in any of claims 14 to 16, in which the cladding region of the microstructured-fibre portion comprises a first cladding region comprising a plurality of elongate holes, and a second cladding region.

18. A fibre as claimed in claim 17, in which the second cladding region is solid.

19. A fibre as claimed in claim 17, in which the second cladding region comprises a plurality of elongate holes.

20. A fibre as claimed in any of claims 17 to 19, in which the first cladding region, the core region of the microstructured-fibre portion and the core region of the standard-fibre portion all have a higher bulk refractive

index than the bulk refractive index of the second cladding region.

21. A fibre as claimed in claim 20, in which the cladding region of the microstructured portion includes a further cladding region, which surrounds the second cladding region.

22. A fibre as claimed in any of claims 17 to 20, in which the core region of the microstructured-fibre portion and the core region of the collapsed-fibre portion each have a higher bulk refractive index than the bulk refractive index of the first and second cladding regions.

23. A fibre as claimed in any of claims 17 to 22, in which the collapsed-fibre portion is comprised in a standard-fibre device.

24. A fibre as claimed in any of claims 14 to 23, having a standard-fibre portion at each end.

25. A method of transferring light from a microstructured fibre to a standard fibre, the method comprising the step of propagating the light along a fibre as claimed in any of claims 14 to 23.

26. A microstructured optical fibre, comprising an inner region of material having a first, higher bulk refractive index and an outer region of a material having a second, lower bulk refractive index, the fibre also comprising a plurality of elongate holes that provide the predominant guiding mechanism in the fibre, such that, in use, the holes influence propagation in the fibre to the extent that collapse of the holes would cause the spot size of a mode guided at a wavelength of operation to change by more than 20%.

27. A microstructured fibre for supporting a guided mode, the fibre comprising an inner region comprising material having a first, higher bulk refractive index, and a region, surrounding the inner region, having a second, lower bulk refractive index and comprising a plurality of elongate holes that provide the predominant guidance mechanism in the fibre, such that, in use, more than 90% of the power of the

guided mode propagates at a wavelength of operation, within the inner region.

28. A microstructured fibre comprising (i) a core region, (ii) a cladding region including a plurality of elongate holes, (iii) a higher-index zone that comprises dielectric material having a first, higher bulk refractive index and (iv) a lower-index zone that surrounds the higher-index zone and comprises dielectric material having a second, lower bulk refractive index, characterised in that the holes are arranged to confine light to the core region of the fibre.

29. A method substantially as herein described with reference to the accompanying drawings.

30. An optical device substantially as herein described, with reference to the accompanying drawings.

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Claims searched:	1-25, 29	**Date of search:**	30 July 2002

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Search Report under Section 17

Databases searched:

UK Patent Office collections, including GB, EP, WO & US patent specifications, in:

UK Cl (Ed.T): G2J(JGBP)

Int Cl (Ed.7): G02B

Other: Online: WPI, EPODOC, JAPIO

Documents considered to be relevant:

Category	Identity of document and relevant passage	Relevant to claims
X, E	EP 1199582 A1 (LT) Fig 1b	1, 14 at least
X	WO 00/49435 A1 (UNIV OF BATH) Figs 6, 9 ,10	"
"	WO 00/16141 A1 (CORNING) Fig 2	"

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